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X-ray Optics Research for the Linac Coherent Light Source: Interaction of Ultra-short X-ray Laser Pulses with Optical Materials

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Abstract. Free electron lasers operating in the 0.1 to 1.5 nm wavelength have been proposed for the Stanford Linear Accelerator Center and DESY (Germany). The unprecedented brightness and associated fluence predicted for pulses <300 fs pose new challenges for optical components. A criterion for optical component design is required, implying an understanding of x-ray – matter interactions at these extreme conditions. In our experimental effort, the extreme conditions are simulated by currently available sources ranging from optical lasers, through x-ray lasers (at 14.7 nm) down to K-alpha sources (~0.15 nm). In this paper we present an overview of our research program, including (a) Results from the experimental campaign at a short pulse (100 fs – 5 ps) power laser at 800 nm, (b) K$-\alpha$ experiments, and (c) Computer modeling and experimental project using a tabletop high brightness ps x-ray laser at the Lawrence Livermore National Laboratory.

1. INTRODUCTION

The development of modern high power laser facilities in XUV regime brings new opportunities for the research of basic physical processes involved in the x-ray – matter interaction. In turn, it also poses new challenges on optical components. For example, at the Linac Coherent Light Source, the projected brightness and associated non-focused fluence (up to 30 J.cm^{-2}) in <300 fs will be available in 2008 and at the TESLA source (DESY) the focus intensities of 10^{19} W/cm^2 in 100 fs pulses will be achievable in 2011.

Interaction experiments have been performed at many laser facilities, e.g. [1–4] in (near-) visible wavelength range or in XUV range [5] using a quasi-steady-state long pulse x-ray laser (XRL). At the LLNL the research involves the interaction of x-ray pulses with various materials from sources available nowadays. In these proceedings

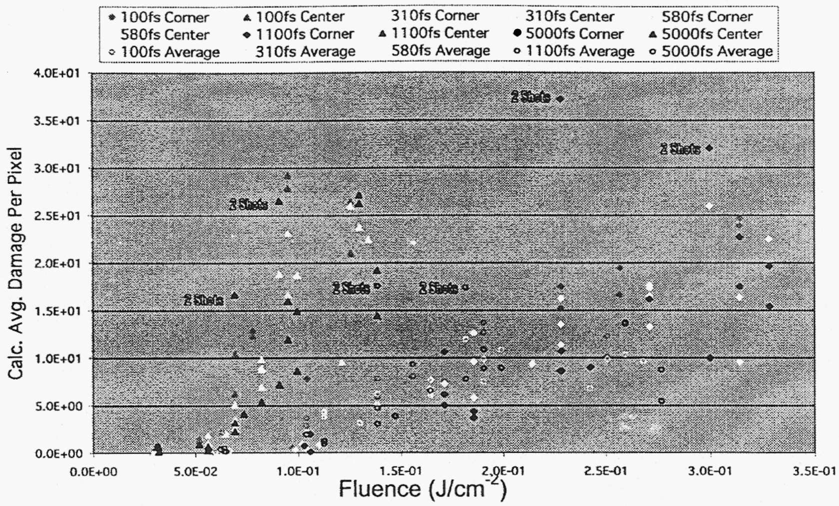


FIGURE 1. Irreversible damage at fluences as low as ~0.1 J.cm^{-2} with no dependence on pulse length was observed. High power short pulse duration laser experiment at 800 nm carried out in 2001.

we present our results, numerical modeling and experimental projects on the three major paths being pursued at the LLNL.

2. EXPERIMENTS AND SIMULATIONS
A. Damage by 800-nm Laser Pulses

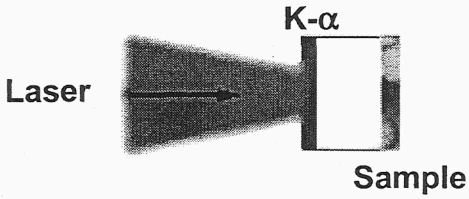
The experiments at the USP facility in 2001 used pulse durations from 5 ps down to 100 fs with energies up to 3 J (i.e. focused fluxes up to ~0.3 J.cm^{-2}) at 800 nm interacting with silicon wafer targets. The data (Fig. 1) show clearly observable irreversible damage at fluences as low as ~0.1 J.cm^{-2}, with no dependence on intensity (the pulse duration was varied by a factor of more that 100 while keeping the energy constant; the damage onset fluence remained unchanged).

Nowadays, no reliable modeling of the interaction exists. Recently, a German group has now repeated our experiment and found the same results [6], also with no explanation. R. London, S. Rubenchik, and M. Feit of the LLNL are currently developing a theoretical model.

B – Damage by a K–α source

The second type of x-ray – matter interaction experiments involves the use of a K–α source generated by a short (~100 fs) laser pulse. The target materials range from Cu (8.0 keV) to Al (1.5 keV). The projected experiment will use such a K–α source to irradiate (in back-emission) a sample material (Fig. 2). The advantages of this scheme consist in a short wavelength comparable with the projected X-FEL facilities, and short pulse duration achievable. The scheme, however, requires basic research to produce reliable and well-described K–α sources.

Preliminary experiments at ATLAS 10 (Max-Planck-Institut, Germany) and JanUSP (LLNL) facilities were carried out in order to develop and characterize various K–α sources. Comparison in Fig. 3 shows the optimization of the laser intensity to maximize the K–α output (cf. also [7]). In our experiments we obtained up to 3.7×10^9 photons per sterrad (supposing an isotropic K–α distribution).



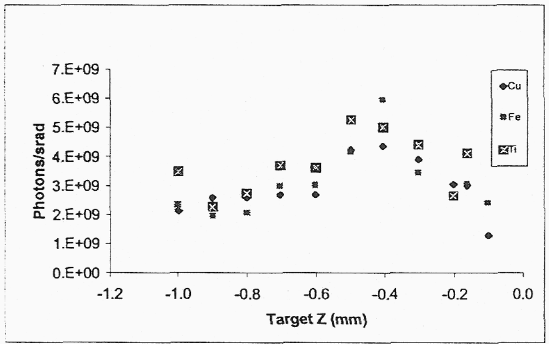
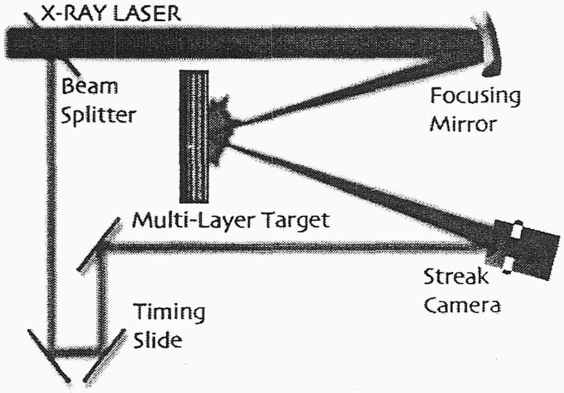


FIGURE 2. In a proposed experiment x-ray radiation from a short pulse laser driven K–α source will interact with an investigated sample.
FIGURE 3. K–α source optimization with respect to the laser intensity.

C- Damage by an X-ray Laser

The proposed experimental campaign will concentrate on the interaction of the focused XRL beam provided by the COMET tabletop facility with multi-layer mirrors. These will include Si- and C-based optics, such as Mo:Si or Ru-C, operated under near-normal incidence. The damage will be studied by time-resolved measurement of the reflected beam using an ultra-fast streak camera with resolution up to 300 fs. The reflected pulse will be compared on a shot-to-shot basis with the original pulse, a small portion of which will be sent directly to the streak camera without the focusing and interaction with the target (Fig. 4). This scheme will allow us to evaluate the intensity profile on the target, and to calibrate the spot size (and hence intensity) as a function of the distance between the focusing optics and the target. The experimental work will provide data on reflectivity changes and then by interpretive modeling on material changes both during and after the x-ray pulse.

The hydrodynamic changes that affect mirror properties on intermediate to later times can be currently modeled by the LASNEX and RADEX codes [8]. Preliminary results demonstrating the high sensitivity to small material property changes are shown in Fig. 5, where dynamic photon absorption and subsequent expansion in a Mo/Si multilayer mirror are modeled with the code RADEX. The resulting density profiles were then input into a multilayer optics code to calculate the dynamic reflectivity, which is what will be experimentally measured. By choosing the multilayer period and incident beam angle, substantial changes in reflectivity are predicted. The changes shown take place on hydrodynamic timescales and produce distinct 'signatures' in the multilayer reflectivity as a function of photon energy (or incidence angle) arising from material expansion into vacuum. Other physical effects with different timescales lead to different reflectivity temporal behavior, including



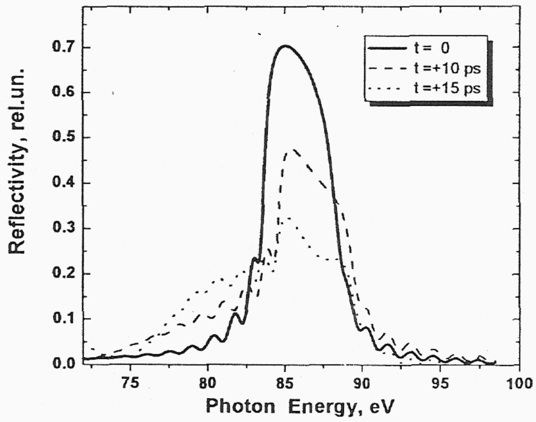


FIGURE 4. Proposed layout for an experiment on focused XRL beam interaction with multi-layer mirror samples.

FIGURE 5. Modeling of the X-ray reflectivity of a Mo/Si multilayer mirror under the incidence angle of 8 degrees (50 pairs, 30Å Mo/45Å Si on a silicon substrate), where t=0 is the beginning of the incident laser pulse: duration 5 ps at FWHM, intensity 1.7 10^{11} W/cm^2, photon energy 84 eV.

changes seen only after the x-ray pulse is over. For example one might find improvements in reflectivity on subsequent shots, as a result of smoothing. The preliminary theoretical analysis predicts in some conditions the occurrence of phase transitions like melting on (sub-)ps timescales.

CONCLUSIONS

In this paper we presented the experimental program and associated simulations on x-ray – matter interaction that is being carried out at the Lawrence Livermore National Laboratory. In a surrogate experiment with a short pulse (100 fs – 5 ps) power laser at 800 nm we demonstrated irreversible changes in a silicon target at fluences as low as 0.1 J/cm^2. No reliable modeling exists so far.

In frame of the __α program, we optimized __α sources from different targets. In our further work these __α sources will be used to investigate the interaction of a sample with this short x-ray pulse.

Finally, the XRL project was presented where the focused short pulse transient XRL will interact with a multi-layer mirror target. The simulations predict substantial changes in reflectivity of this resonance system.

REFERENCES

[1] J. Larsson et al., App Phys **A 66**, 587 (1998)
[2] A. M. Lindenberg et al., Phys. Rev. Lett. **84**, 111 (2000)
[3] K. Sokolowski-Tinten et al., Phys. Rev. **B 51**, 186 (1995)
[4] D. A. Reis, Phys. Rev. Lett. **86**, 3072 (2001)
[5] B. J. MacGowan et al., Journal of X-Ray Science and Technology **3** (1993) 231
[6] J. Bonse et al., Appl. Phys. **A74**, (2002) 19
[7] Ch. Reich, Phys. Rev. Lett. **84**, 4846 (2000)
[8] Yu.V. Afanasiev, V.N. Shlyaptsev et al., J. of Sov. Laser Research **10**, 1 (1989)

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